Hydro-socio-economic implications for water management strategies: the case of Roussillon coastal aquifer

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Abstract

In many Mediterranean coastal areas, agriculture, drinking water supply, tourism and industry strongly depend on the available groundwater resources. As a result of the significant economic development during the last three decades along the coast, abstractions from coastal aquifers have increased tremendously, frequently leading to overexploitation and saltwater intrusion. Geological, hydrogeological and socio-economical studies as a multidisciplinary approach on a coastal Mediterranean aquifer- the Roussillon - have been carried out in order to design effective water management strategies on areas sensitive to seawater intrusion risk. Geology provides geometry and architecture of the different aquifers, hydrogeology assess the seawater intrusion risk while socio-economic study includes consulting the stakeholders with the aim of suggesting water management and policy option acceptable to the majority of population. This paper then highlights the economic interests at stake, diversity of viewpoints expressed by stakeholders and political dimension of the issue, which are likely to be encountered for all similar situations on both sides of the Mediterranean Sea.

Introduction

In many Mediterranean coastal areas, agriculture, drinking water supply, tourism, and industry strongly depend on groundwater resources. As a result of the significant economic development during the last three decades along the Mediterranean coast (tourism development, population migration, agriculture intensification), abstractions from coastal aquifers have increased tremendously. This has often resulted in significant decline of water tables which have, depending on the local geological context, increased the risk of seawater intrusion. Given that Mediterranean coastal aquifers are generally complex multi-layer systems, assessing the significance of seawater intrusion risk often remains a difficult exercise requiring extensive knowledge of the geology and the hydraulic conditions of the aquifer, both inland and at sea. This paper illustrates, through a French case study, how the risk of seawater intrusion can be assessed, using reservoir geology methods: onshore, through genetic stratigraphy and offshore, through seismic stratigraphy. The paper also shows that, as long as this risk is not assessed precisely, stakeholders may have very different attitudes and promote very different strategies for ensuring sustainable groundwater management. These different visions clearly reflect the economic and political interest at stake.
The case study area selected for carrying out this interdisciplinary approach is the Roussillon basin, located along the southernmost part of the French Mediterranean coast, near the

Spanish border. This 700 square kilometres sedimentary basin is bordered by the foothills of the Pyrenean Mountains to the South, the Corbières karst region to the North and the Mediterranean Sea to the East (figure 1). Groundwater resources comprise several Pliocene confined aquifers, which are overlain by a Quaternary deposits aquifer and embedded within a Miocene structured margin (figure 1). These aquifers are intensively used for drinking water purpose, for tourism related activities along the coast and by agriculture for irrigating orchards and vegetables crops. As the superficial aquifer was getting more and more affected by diffuse pollution (nitrates and pesticides), the Pliocene aquifers have been increasingly exploited, in particular by municipalities but also by large vegetable producers. The resulting decline of water tables which has been observed during the last 20 to 30 years (figure 3) is expected to continue as the population keeps growing and the farming sector progressively leaves ancient surface canal irrigation systems to drilling well irrigation.
Although it has not yet been proved that seawater intrusion actually take place in the present situation, this threat is likely to increase in the coming years. Policy makers therefore consider as urgent to improve the knowledge of the structure and functioning of the Pliocene aquifers and to identify possible strategies to mitigate the risk of groundwater deterioration. The hydro-socioeconomic result presented in this paper is an attempt to answer to this policy demand.

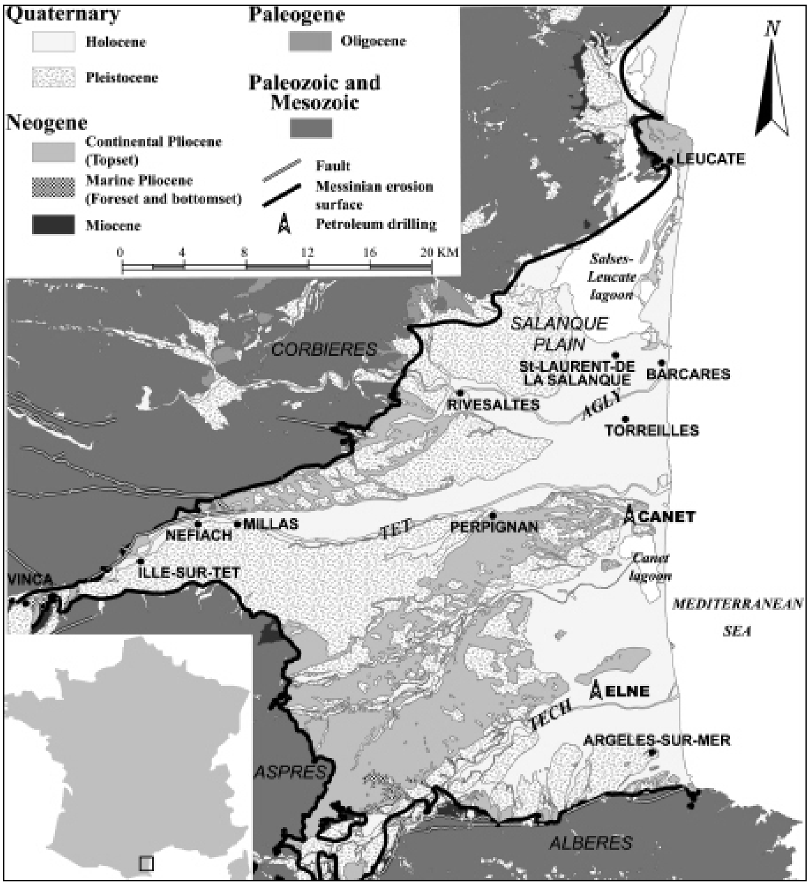

Figure 1: Location of the Roussillon basin

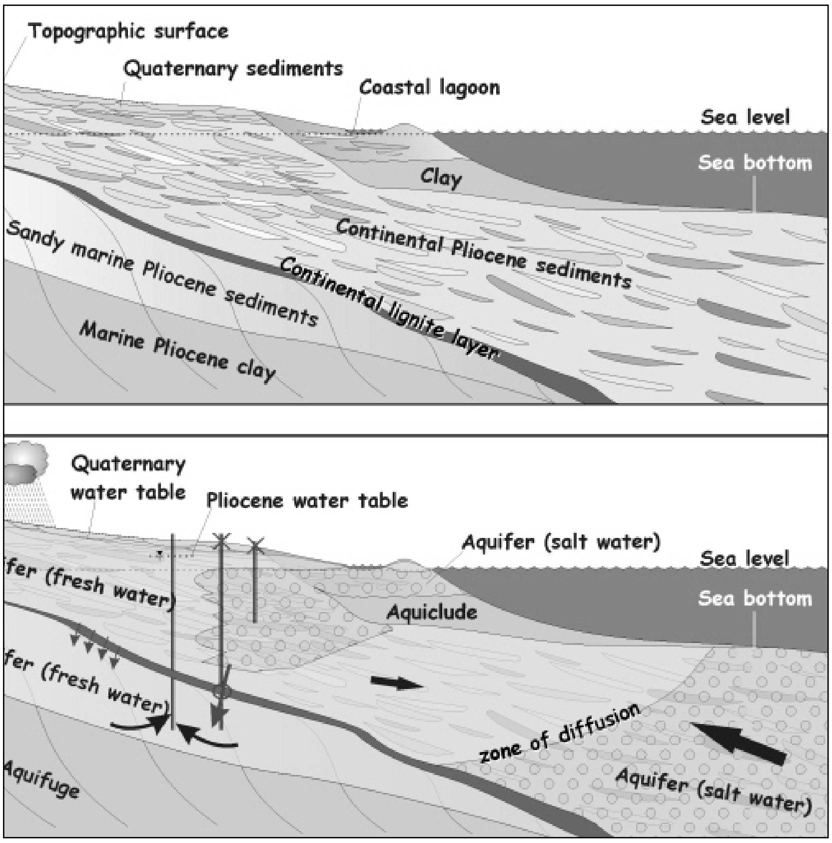

Figure 2: Geological (1) - hydrogeological (2) cross sections of the Roussillon basin. Vertical leakage linked to hydraulic head inversion is illustrated on the hydrogeological cross section. Vertical leakage takes place through more sandy continental lignite layer or through defective boreholes. Scale and location are not presented because these theoretical cross sections only illustrate hydrogeological problematic.

Assessing the risk of seawater intrusion

Seawater intrusion is a complex problem in which the study of geology is as important as hydrogeology because of determining boundaries conditions and knowing interconnections between the different coastal aquifers. Consequently, regional geology must be perfectly known before beginning hydrogeological investigations. Then, appropriate hydrogeological method can be determined with the aim of assessing the risk of seawater intrusion.

Geology of the case study

First step of the developed methodology is to put back the studied area in a regional geological framework. During the Late Miocene, there was a marine regression following the Messinian salinity crisis (partial drying of the Mediterranean Sea; approximately 5.8 M.y.). A major phase of erosion induced depression of the fluvial networks and the deep canyons that have been identified in the Roussillon (Clauzon et al., 1987). During the Pliocene (5.3 M.y.), the opening of the Gibraltar Straits (only connection between Mediterranean sea and Atlantic Ocean) enabled the seawater to return which penetrated the deep valleys and transformed the Roussillon basin into a ria (fluvial canyon drowned by the marine transgression). All the onshore Pliocene sediments were deposited within 1.7 M.y. (i.e. 75 cm/1000 years – (Clauzon et al., 1987)).
The Quaternary deposits were due to the interglacial transgression and regression phases. The last transgression (sea-level rise) resulted in some coastal constructions and a lagoon area from Leucate to Argelès. Today only the Salses-Leucate and Canet lagoons remain.
A detailed lithological and geometric geological model of this basin has been built mainly on

the basis of reservoir geology methods (Duvail *et al.*, 2005): (i) onshore, through genetic stratigraphy performed with BRGM public underground database (more than 500 wells, with about 120 logging), the interpretations of well logging, and cross checking the outcrops, (ii) off-shore, through seismic stratigraphy (existing oil companies sections and high-resolution seismic profiles from University of Perpignan).

A detailed mapping of the elevation of the top and bottom of the aquifers, the aquitards and aquicludes along with their lithology, their interrelationship with other aquifers (especially karstic, whose structure is also influenced by the sea level variations, have been studied) is thus available. Lithological and geometrical knowledge of the aquifers mainly allows us to determine if coastal aquifers are directly or indirectly connected to the Mediterranean Sea.

Hydrogeology of the case study

Second step of the processes aims at determining the link between geology and hydrogeology of the studied area. The Roussillon basin contains three main kinds of aquifers (from bottom to top: Quaternary aquifer, continental Pliocene aquifer and sandy marine Pliocene aquifer). Several little size aquifers could compose each aquifer kind. For instance, stacks of five different sedimentary prisms (sand and clay) constitute marine pliocene sediments.

Quaternary aquifers are mainly composed of alluviums (conglomerate, flood plain) and coastal deposits whose geometry is linked to the Pliocene-Quaternary glacio-eustatic variations. The unconfined Quaternary aquifer lies along the main rivers and the coastline. It is mainly exploited by farmers, private individual and camping owners. Water quality of the Quaternary upper aquifer is bad near the coast due to a high chloride concentration (e.g.: electrical conductivity can reach 5000 mS/cm at St-Laurent-de-la-Salanque - 5 km from the coastline).

The Pliocene aquifers (continental and marine), whose characteristics are linked to the Messinian event are built of fluvial deposits and marine sands and clays. Many wells of these aquifers were artesian thirty years ago. Now, artesian flowing wells are more and more uncommon. The confined Pliocene aquifers are mainly exploited for drinking-water supply and by farmers. Generally, both water quality and hydraulic head of the Pliocene aquifer increase with the depth of the exploiting well. Even under the beach barrier sand, water conserves a good quality: chloride concentrations are lower than 40 mg/l. Locally, some interconnections exist between the Quaternary and Pliocene aquifers, mainly because of two reasons: (i) leakage from pre-existing wells, (ii) incision of shift Pliocene aquifer by Quaternary channels. These interconnections tend towards decreasing Pliocene aquifers water quality.

Fluvial sands fill distributaries channels of deltaic complex constitute the **Continental Pliocene aquifer**. This aquifer contains excessive water mineralization only in the northern part of the basin, along the lagoon and even more so along the coast at Barcares. The continental Pliocene aquifer is very productive, especially in Salanque plain. Because of its geological building (stream channel and flood plain alternations), this aquifer is considered like a heterogeneous aquifer: permeability tensor and salt water interface position could extremely vary in the three dimensions.

Usually, layers of lignite with plants remains alternating with marsh plastic clays that are located beneath the Continental Pliocene aquifer. This non-continuous impervious layer separates continental Pliocene aquifer from sandy marine Pliocene aquifer.

Sandy marine Pliocene sediments correspond to the prograding deltaic shore face. Theoretically, this homogeneous aquifer is not connected to the sea and it is preserved from seawater intrusion. However, some area contains excessive mineralization. The origin of the contamination is the vertical leakage from the partially contaminated Quaternary aquifers to the Pliocene aquifers due to existence of defective boreholes. New boreholes drilled next to the old ones show a strong decrease in the water's salt content. Without any water pumping, hydraulic head of the sandy marine Pliocene aquifer is higher than the continental Pliocene aquifer.

Increasing of salt water intrusion risk

According to electrical conductivity measurements and chemical analysis (fig. 3), seawater intrusion is well recognized in the Salanque plain few kilometres from the coast relating to the unconfined superficial Quaternary aquifers. In the South Roussillon basin, seawater intrusion is restricted within one kilometre of the coastline.

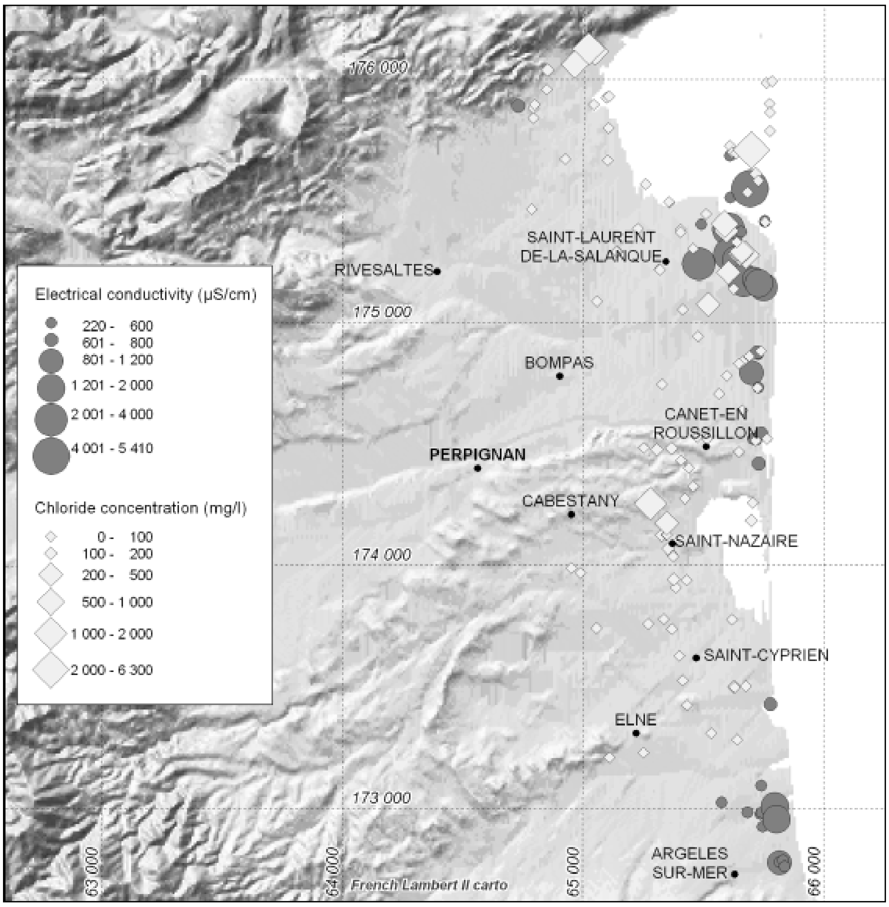

Figure 3: Coastal water quality in September 2004. Values of electrical conductivity provide from unconfined superficial aquifer and chloride concentration from confined aquifers. In the north of Roussillon, Salanque plain coastal area is more vulnerable to decrease of water quality because of the Salses-Leucate lagoon presence, high hydraulic conductivity and large number of drilling wells including defective boreholes. In the southern Roussillon, water quality decreases only in the unconfined superficial aquifer in few places close to the sea (campsites with superficial borehole).

Near the coast and since the beginning of exploitation, Pliocene aquifers water level have reached 0 meter more and more often during the year (fig. 4). Moreover, annual variations range increases year after year. Although abstractions are almost constant in the Quaternary aquifers, they have tripled for Pliocene aquifers since 1975 (Accord cadre, 2003). Groundwater levels drop means that leakage direction and vertical flow are reversed: leakage was upward before exploitation, leakage is downward actually. Even, if no direct connections exist between sea and Pliocene aquifers, the risk of seawater intrusion is real because of vertical flows through the contaminated superficial Quaternary aquifers. In the same way, chlorides concentration increase locally in a few observations points located in the Pliocene aquifer. Actually, these increases are geographically limited, but they are also continuous for each observed point.

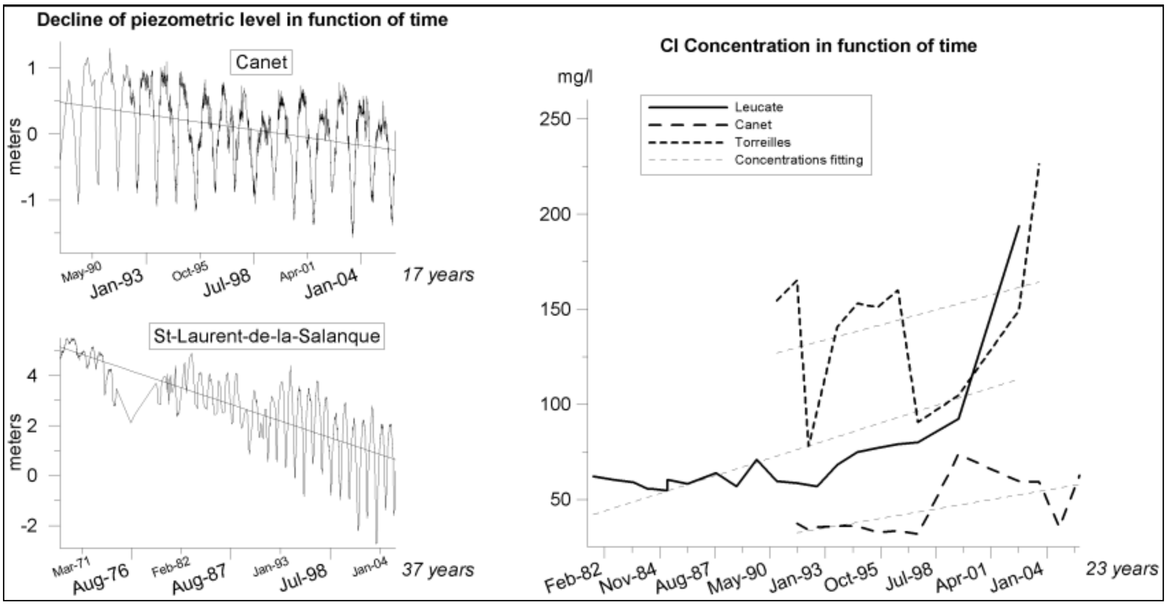

Figure 4: Piezometric level and chloride concentration both in function of time. All these observations points are located in the Pliocene aquifers near the sea.

Today, the situation is serious but not totally irreversible. Nevertheless, after field observations, field measurement and geological studies some quantitative hydrogeological studies must be aimed at determining the exploitation way of the Roussillon aquifers. These quantitative hydrogeological studies have begun by variable-density flow and solute transport simulations. In these simulations, because of the geological knowledge, interconnection and aquifers geometry constitute some preponderant parameters. In the same way of copying geological reality, the distribution knowledge of hydraulic conductivity comes from classical well pumping tests and from geostatistical stress analysis of the geological model of Roussillon plain. The aim of modelling is to determine amongst other thing, the time and velocity of vertical leakage.
Such studies allow determining aquifers vulnerability to seawater intrusion in different coastal area. The saltwater intrusion risk may be assessed for the present time and for water management scenarios. For example, in Salanque plain, because of a specific geology whose origin is attributed to a differential subsidence, the seawater intrusion risk is more pronounced than in the South of the Roussillon basin. Regarding hydrogeological results, water management advices will be different for each aquifer. These advices resulting from geological and hydrogeological model need to be confronted with stakeholders' opinions about the ways of ensuring a sustainable water management.

Identifying water management scenarios through stakeholders consultation

Because stakeholders have different technical background, information levels, interests at stakes and strategic objectives, they have diverging opinions on the strategy that should be selected for ensuring a sustainable management of the Pliocene coastal aquifer. Taking all these visions into consideration and debating them publicly is the condition for the acceptability of the final decision and successful implementation of the policy option selected. One option for eliciting the diversity of stakeholders vision consists of conducting a stakeholder analysis (Wellard, 1997) using semi-directive individual interviews. These interviews are leaded by a same questionnaire dealing with:

- water management (opinions, preoccupations, …),
- decrease of water quality linked to saltwater intrusion (origin, localisation, interaction between groundwater and surface water, …),
- private borehole intended for irrigation, household, campsite, …
- water use conflicts (beginning, suggested solutions, …)
- reactions about enforcement of regulation tools (tax system, quota, restrictive measure for implanting new borehole, fine, …)

This section presents the result of such a consultation conducted in the Roussillon case study area where 35 representatives from public territorial bodies (2), municipalities (9), drinking water utilities (7), farmers' organisation (4), private companies (2), regional research department and local expert in hydrogeology (7) and government agencies (4) were interviewed. Qualitative summary of the answers is presented below.

Stakeholders perception of the risk of seawater intrusion

The results of this consultation highlight that stakeholders do not share the same vision of the risk of seawater intrusion, its significance in the current situation, its origin and its possible consequences in the future. Although all of them acknowledge that the water table has been dropping for several decades, some of them do not perceive this as a serious threat. They argue that the drop of water table is not likely to generate seawater intrusion as there could be an impervious layer between the sea and the Pliocene aquifer preventing seawater inflow – if this layer is geologically confirmed; it is not a vertical and horizontal continuous layer all along the shoreline. Similarly, most of the stakeholders are aware that high chloride concentrations have been found in several boreholes along the coast but their opinion on the origin of the contamination differ: for some of them, the presence of chloride confirms that intrusion actually take place, whereas others assert that chlorides found are coming from the brackish water contained in the superficial quaternary deposits through abandoned boreholes. This statement suggests that stakeholders are likely to remain entrenched in their beliefs and vision, and that no real debate might take place as long as these key technical questions will not be solved by scientific and technical experts and transferred to the public.

Alternative water management strategies advocated

As they do not agree on the nature and the intensity of the problem, the solutions they advocate significantly differ. A first group of actors call for an immediate and drastic reduction of groundwater abstraction. Others oppose to this decision and simply recommend that the monitoring of chloride concentration be strengthened and the control of existing boreholes reinforced both in terms of monitoring of water abstractions and compliance of the works with construction quality standards (to reduce the risk of contamination of deep layers with superficial contaminants). Similarly, although all stakeholders agree that the quantitative pressure exerted on the aquifer will continue to increase in the coming years, mainly due to sustained population growth, they disagree on the policy that should be developed at the regional level to meet the mounting water demand. The following three main strategies are advocated, reflecting the diversity of interests at stake.
The first strategy is based on the assumption that the satisfaction of increasing drinking water supply should be considered as a priority objective overruling all other objectives – agriculture development in particular. The Pliocene aquifer should only be used for drinking water use and its use for irrigation in agriculture restricted. This would require developing additional surface water supply for agriculture use: three reservoirs (Caramany, Vinça and Villeneuve de la

Raho) could be used as a substitute to groundwater; inter-basin transfer is also quoted as a possible solution that could be implemented with the construction of an aqueduct supplying raw water taken from the Rhône river. The success of this strategy would however necessitate that public authorities be able to identify all existing boreholes (most of them are not officially registered), that appropriate regulation be developed to allow the closure of existing wells (and possibly financial compensation allocated) and that local politicians be willing to support this unpalatable decision.
A second strategy would consists in preserving all existing agricultural and drinking water supply boreholes and allocating them water use quotas corresponding to their current exploitation level (or slightly below if hydrogeological studies confirm that the total abstraction has to be reduced). New drinking water demand would be satisfied through the development of non conventional resources (desalination) or inter-basin transfers (import of water from the nearby Corbières karst aquifer, aqueduct ringing water from the Rhône river). The successful implementation of this strategy would require carrying out a census of existing boreholes, register them, install meters and monitor the implementation of the quota system.
An alternative to the two previous strategies would consist implementing water demand management actions targeting both agriculture and the drinking water sector. Irrigation efficiency could significantly be increased for a large number of farms who still use basin or furrow irrigation techniques (Salanque region). Significant water savings could also be achieved in the drinking water sector through various actions such as reduction of leakages in mains distribution systems; installation by households and public services of water saving devices such as double button toilet flushes etc.; provide economic incentives for reducing households per capita water use through increased water pricing; reduce irrigation public gardens; develop waste water recycling systems for irrigating golf greens, public gardens, etc.

The socio- political implications

The implementation of any of the strategies described above would however be difficult due to political and economic constraints. For instance, the reduction of groundwater use by the farming sector is a very sensitive political issue: farmers strongly oppose to any restriction of their access to the aquifer; they have only accepted after long negotiation that a census of agricultural wells be carried out; water meters remain very rare although this is required by the law since 1997; and they are generally opposed to the idea of substituting surface water resources to groundwater, as this alternative would probably be more costly, its supply less flexible and water of lower quality. Many stakeholders also oppose to considering that drinking water supply be considered as a priority as long as no water saving efforts have been made in this sector: between 25 and 50% losses occur in drinking water networks, huge volumes of water pumped in the Pliocene are used for watering lawns or golf courses and filling swimming pool. Some stakeholders also point out that many households have drilled private wells to access the Pliocene aquifer (region of Perpignan) and that these should be regulated in priority. Building a political consensus will require a significant negotiation effort and the water management policy that may be adopted by all the parties will probably be a compromise of the three options described above.

Conclusion

Salt water intrusion in the Roussillon coastal aquifers could slow down in the case of reasoned water management: reducing water abstraction, diversifying water resources, taking care with borehole quality, … However, all the proposed recommendations must be in line with the hydrogeological and socio-economical context of the Roussillon basin.

From a multidisciplinary approach, high-resolution geology of sedimentary prisms allows a better understanding of coastal aquifers. It makes it possible to have a precise geometry of the aquifers and aquicludes. This knowledge establishes the relations existing between the different aquifers and the possible connection to the sea. It contributes to establish the origin of salinity of contaminated boreholes or aquifers in such a complex multi-layer aquifer. Indeed, it is possible to determine whether if direct or indirect (defective boreholes) connection with sea exists. Understanding of the geological framework, hydrogeological field observation measurements and modelling allow the determination of the degree of vulnerability to seawater intrusion. In this way, socio-economic studies are able to give some suggestions related to water management befitting the geological and hydrogeological context of the studied area, considering the different points of views of the stakeholders.

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